Optical Plume Anomaly Detection—Engine Diagnostic Filtering System

Anita E. Cooper/EB22
205–544–4423
E-mail: anita.cooper@msfc.nasa.gov

The development and testing of new sensor capabilities to address the increasing demands for rapid assessment of rocket engine health has led to the use of plume emission spectroscopy and advanced data analysis techniques. Several years ago, the Space Shuttle Main Engine (SSME) became the subject of a project at MSFC to look at techniques for detecting anomalies in the operation of rocket engines through observation of the exhaust plume. Since then, plume emission spectroscopy has recorded many nominal tests, and the qualitative spectral features of the SSME plume are now well-established, leading to definition of the optical plume anomaly detection (OPAD) system.

The operational health of an engine is examined through the acquisition of spectrally resolved plume emissions and the subsequent identification of abnormal emission levels in the plume indicative of engine degradation or component failure. Since the amount of energy emitted from the plume due to radiation of a given species becomes a highly nonlinear function with increased specie concentration >> hardware erosion, development of a process necessary to define these abnormal emission levels presents numerous challenges. The optical plume anomaly detection-engine diagnostic filtering system (OPAD–EDIFIS) is the defined process to accomplish the tasks. OPAD–EDIFIS will make analysis fast, reliable, and readily adaptable to other rocket engines.

OPAD–EDIFIS is a comprehensive/ complex platform of various modules representing the combined efforts of MSFC, Ames Research Center (ARC), the Air Force's Arnold Engineering Development Center (AEDC) at Tullahoma, Tennessee, University of Alabama at both Tuscaloosa and Huntsville, Dr. Wray Buntine, an ARC subcontractor, and T. L. Wallace, a graduate student. In its present form, it embodies gigabytes of code/data with various graphical display capabilities. The "real-time" version(s), currently under development, will exist as a stand-alone subset of the EDIFIS.

Basically, the analytical modules consist of:
- Preprocessing codes;
- Spectral codes;
- Neural networks; and
- An optimization/fitting routine.

A typical spectrum generated has three components: A dominant component due to both equilibrium and chemilumenescent emission of the OH molecule generated by the hydrogen burning SSME; a background continuum component due to an unbound state of H_2O and the unavoidable measurement of scattered background light; and possibly a metallic component indicating metal erosion. Several metals of interest radiate in the OH region. Unfortunately, the complex interaction of the OH and water vapor emissions are poorly understood and little quantitative data are available that would permit development of an accurate model. Ames Research Center and Dr. Wray Buntine have developed statistical/ filtering preprocessing techniques to address this problem, isolating the metallic components of the spectrum. Figure 96 isolates three metals of interest in test 901–853, engine 0523 failure of HPFTP/AT Unit 6–4 at Stennis Space Center in January, 1996. Elements Cr, Co and Ni are plotted for the test duration. (Saturated lines at shutdown are omitted.)

A line-by-line (LBL) atomic spectral model developed by T.L. Wallace predicts the spectrum for a given metallic species, using inputs such as number density, broadening parameter, temperature and pressure. Recently, the focus of efforts related to this module shifted towards validation of the integrated spectral analysis system and spectral model. In particular, work has been undertaken to validate the radiative transport, self absorption and collisional line-broadening mechanisms, and chemical depletion rates to produce error propagations and uncertainties. Code validation is an essential part of spectral analysis, and is required in order to accurately determine species densities from spectral measurements. In late 1995, the SSME was deliberately seeded with known concentrations of two elements at MSFC's Technology Test-Bed (TTB). (Unfortunately, the TTB was closed before additional seeding tests could be conducted.) Spectral data collected by the OPAD system provided confirmation and essential validation data for the spectral model and data processing methodologies. The success of this validation process was evident in MSFC's contribution to the failure investigation of engine 0523 undergoing tests at SSC. While details of this effort will be reported in upcoming technical conferences, the study to determine mass loss estimates for this failure can be briefly summarized as follows:
- The study made certain assumptions of 100 percent RPL, 100-cm observation path length, uniform distribution of eroding material, and steady-state erosion during each 0.5-sec integration interval;
- The study, due to time constraints, addressed only certain periods of a specified set of erosion events; not all erosion activity was present in the entire test;
- The study quantified two of approximately nine elements identified in the erosion events. SSME seeding data is presently limited to chromium (Cr) and nickel (Ni). Coincidentally, Cr and Ni are primary constituents of the alloys reported lost; and
- Pratt & Whitney measurements of mass loss during post-test hardware tear down and inspection totaled approximately 94.45 grams. The MSFC EDIFIS process predicted 37 grams.

While error and uncertainty analyses are underway, the predicted spectral results are almost indistinguishable from the actual

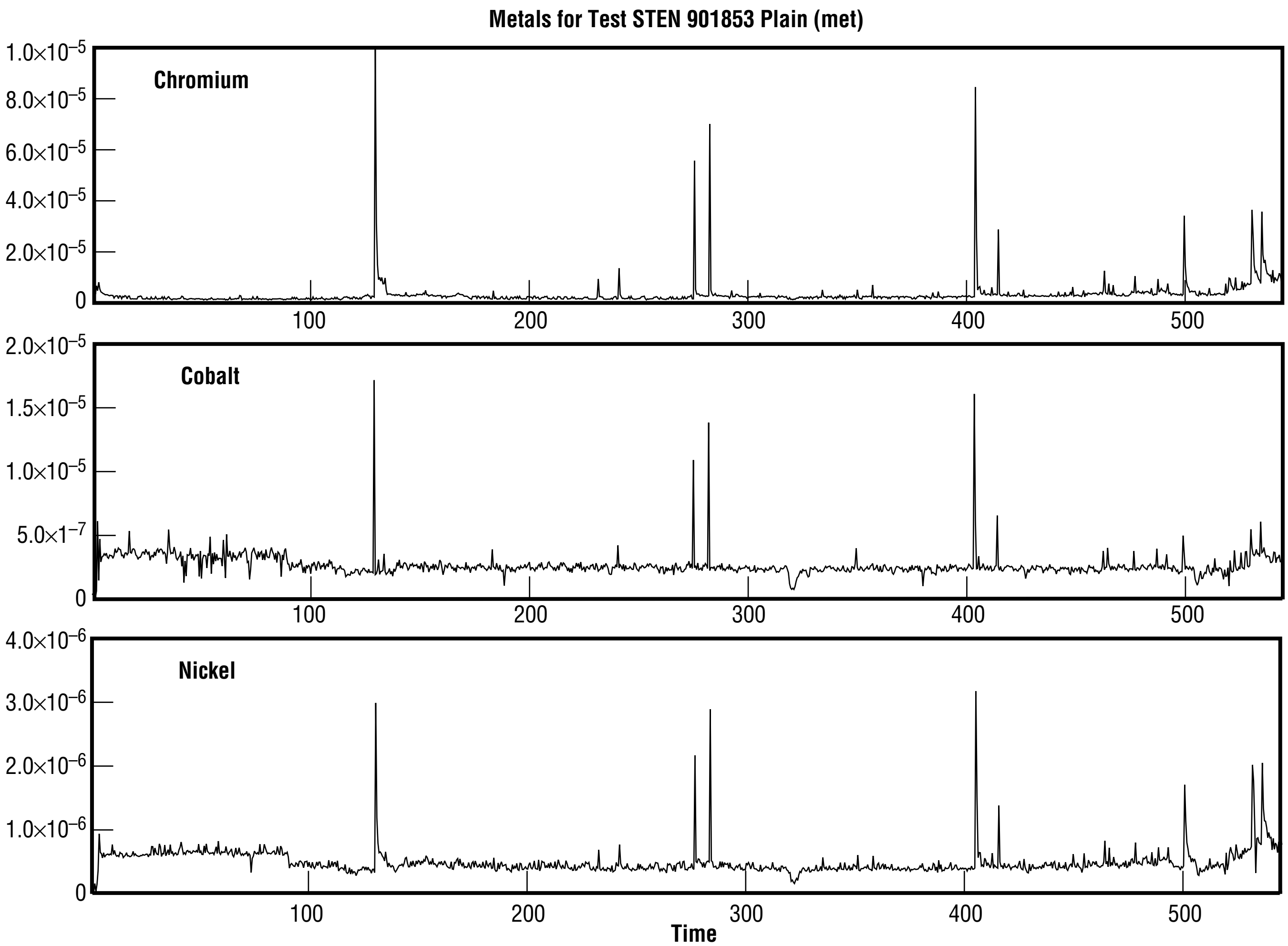

FIGURE 96.—Cr, Co, Ni erosion.

failure event data and rank among the best to date for such complex spectral data.

What is required for the determination of mass loss is the inverse of the spectral model. Given a spectrum, predict combustion temperature and element concentrations (i.e., number density and broadening parameter). The fourth module listed above, optimization-fitting routine, was first used as part of the EDIFIS for the engine 0523 failure investigation. These nonlinear fitting routines on approximately 15 variables using spectral radiation models for 10 atomic species for a total of some 1,500 atomic lines required around 1 hr on an MIPS 8,000 per 0.5 sec of test data, before the fitting converged to approximately 5 percent RMS error. Note the overlay of theoretical versus actual test data in figure 97. While the results are indeed impressive, the computational time requirements have to be addressed for in-flight/real-time systems.

The third module, neural networks, can solve the inverse problem to the spectral model by “learning” how it works. Initially, only minimal accuracy of the neural networks may be required, at which point the optimization/fitting algorithms would complete the predictions. As the EDIFIS work continues, however, neural networks may provide the ultimate solution for in-flight “real-time” applications. The University of Alabama at Tuscaloosa has developed a preliminary set of radial basis function (RBF) networks—one network for each element of interest. This set recently evaluated the entire engine 0523 failure test (which lasted around 553 sec) for seven elements in approximately 2.6 min. Temperature, number density and broadening parameter predictions are plotted for three elements, Cr, Ni and Co, respectively,

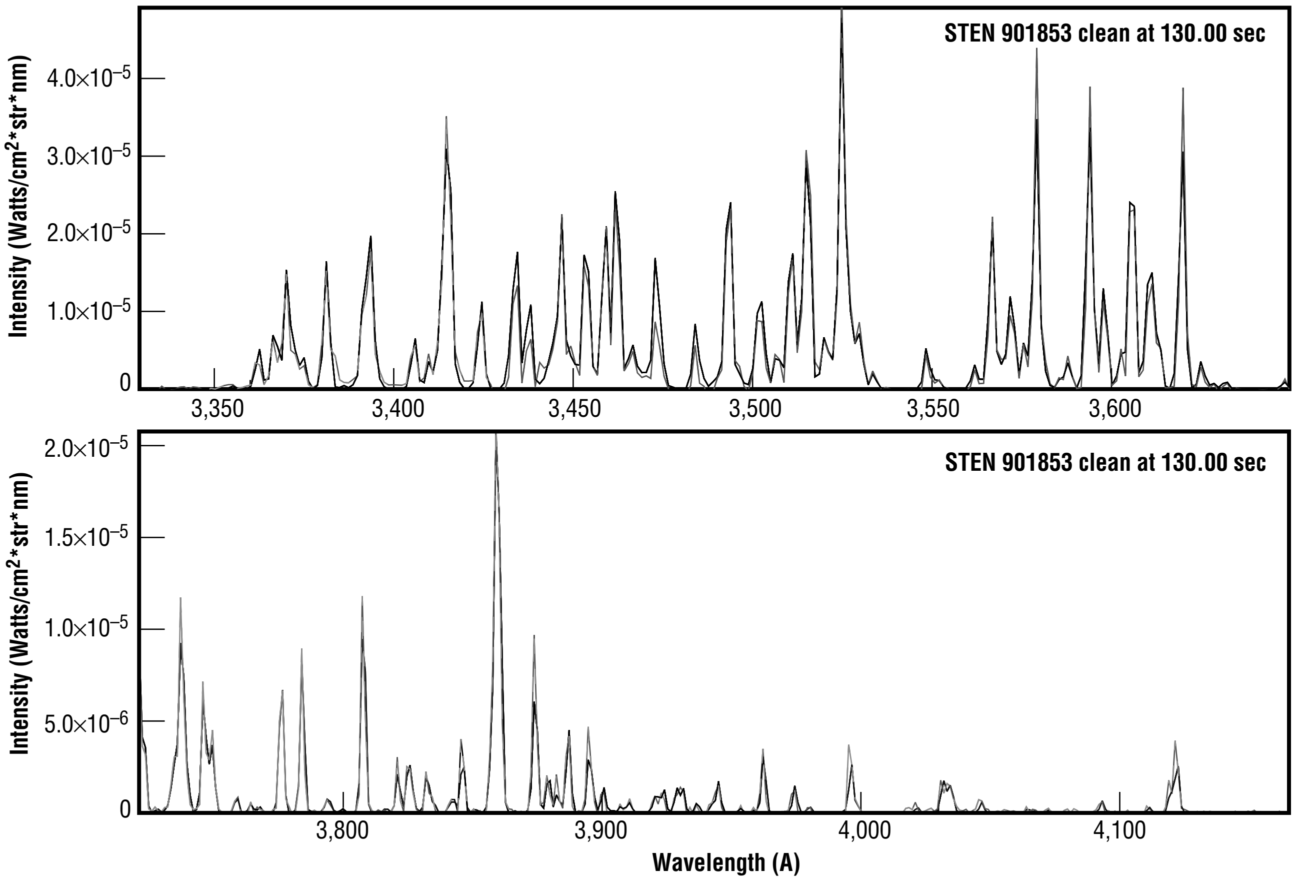

FIGURE 97.—Optimization/fitting results for 130-sec event.

in figure 98. Note from column two of figure 98, when compared to figure 96, how well the neural nets recognize the major events for each of these elements. Improvements in speed and accuracy of the neural networks through the use of better training data can be realized, and such efforts are underway.

Integration of the modules to provide a response time equal to sampling time is a primary goal for the OPAD–EDIFIS system. An investigation is underway by the University of Alabama in Huntsville, Department of Electrical and Computer Engineering, to look at processing improvements through computer architecture and conversion of various software codes into a form which is easily parallelizable.

Wallace, T.L.; Powers, W.T.; and Cooper, A.E.: "Validation of UV-VIS Atomic Spectral Model for Quantitative Prediction of Number Density, Temperature and Broadening Parameter." 1995 JANNAF Exhaust Plume Technology Subcommittee Meeting, October 1995, MSFC, AL (restricted).

Benzing, D.A.; Whitaker, K.W.; and Krishnakumar, K.: "SSME Condition Monitoring Using Neural Networks and Plume Spectral Signatures." AIAA no. 96-2824, Lake Buena Vista, FL, 1996.

Sponsor: NASA Headquarters, Office of Space Science

University/Industry Involvement: University of Alabama, Huntsville; University of Alabama, Tuscaloosa; Vanderbilt University; Tennessee Technological University

Biographical Sketch: Anita Cooper is an electronics engineer in the Instrumentation Branch of the Astrionics Lab at MSFC. She conducts and manages research for the optical plume anomaly detection program to enable development and application of plume spectroscopy technology to rocket engines. Cooper earned her bachelor of science in physics from Athens State College and has worked for NASA for 7 years.

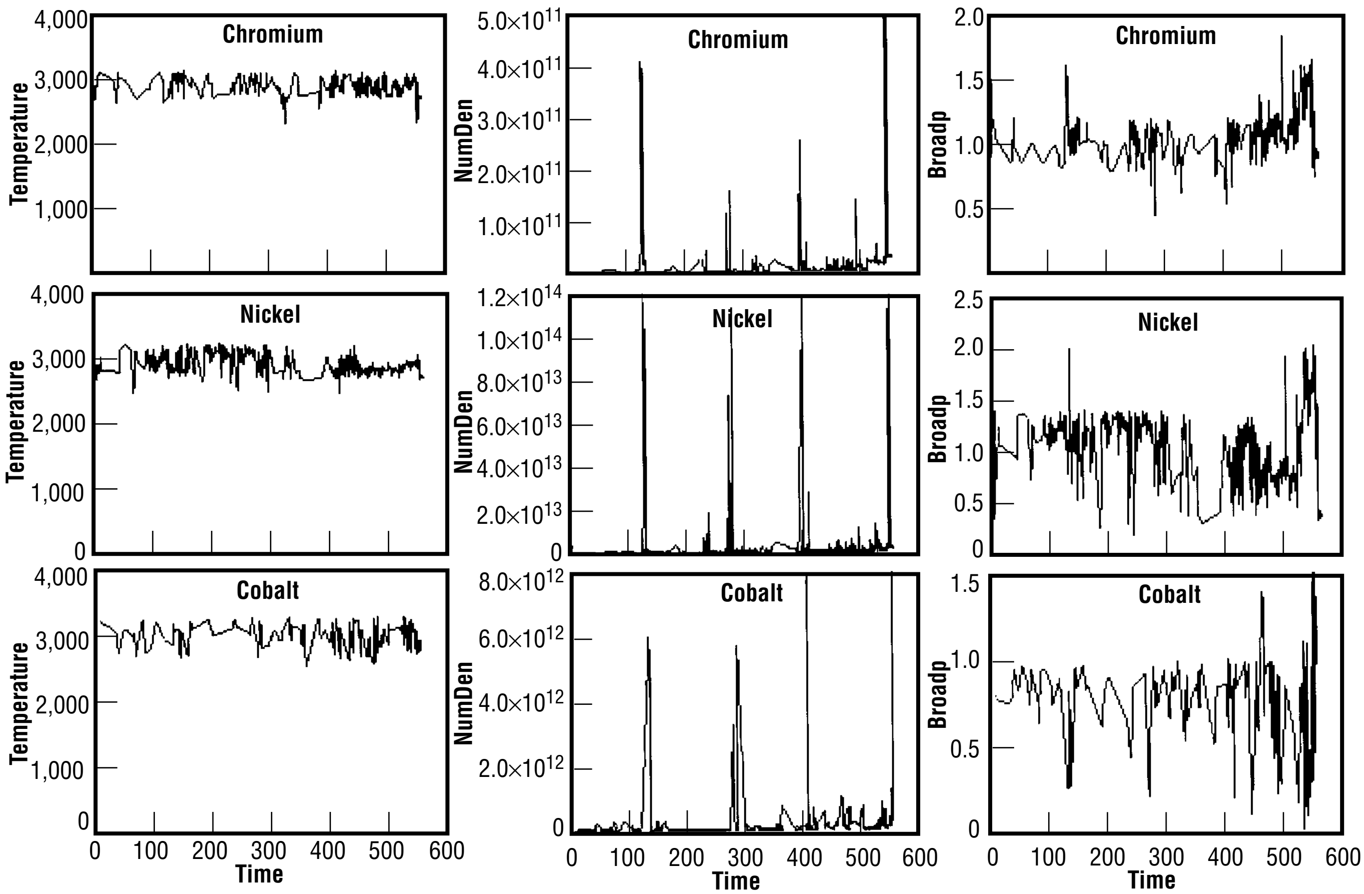

FIGURE 98.—Temperature, number density and broadening parameter neural net results for Cr, Ni, Co.